# Rare Processes and Precision Measurements

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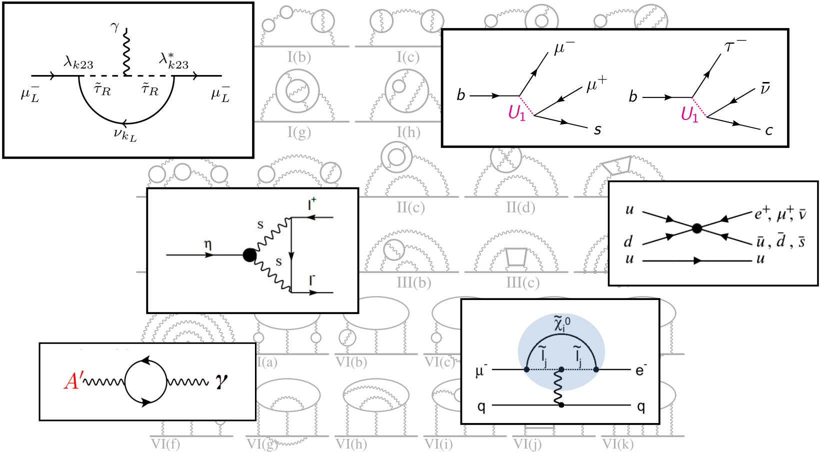
The University of Arizona

Snowmass Computational Frontier Workshop, August 10-11, 2020




Our frontier explores fundamental physics with intense sources and ultra-sensitive detectors. It encompasses seeking tiny deviations from Standard Model expectations in properties and transitions of elementary particle and searches for extremely rare processes.

There are currently several hints for deviations from the Standard Model in measurements within our frontier, including the following:

- Muon and electron $g-2$
- $b \to s\ell^+\ell^-$ decays ($\ell = e, \mu$): $R_K$, $R_{K^*}$, $R_{pK}$, various branching fractions and angular observables
- $b \to c\tau^-\bar{\nu}$ decays: $R(D)$, $R(D^*)$, $R(J/\psi)$
- Inclusive-exclusive discrepancies in $|V_{ub}|$ and $|V_{cb}|$
- $\bar{B}^0_{(s)} \to D^+_{(s)} \{\pi^-, K^-\}$ branching fractions
- First-row CKM unitarity tests
- Neutron lifetime puzzle
- KOTO anomaly in $K_L \to \pi^0\nu\bar{\nu}$

Regardless of whether these particular anomalies will survive, the "rare and precision" way of searching for new physics is very powerful and is often sensitive to mass scales much higher than those directly accessible.

# Organization

Web page: https://snowmass21.org/rare/start

Frontier conveners: Marina Artuso, Bob Bernstein, Alexey A Petrov

| Topical group | Conveners |
|---|---|
| 1: Weak decays of *b* and *c* quarks | Angelo Di Canto, Stefan Meinel |
| 2: Weak decays of strange and light quarks | Evgueni Goudzovski, Emilie Passemar |
| 3: Fundamental Physics in Small Experiments | Tom Blum, Peter Winter |
| 4: Baryon and Lepton Number Violating Processes | Pavel Fileviez Perez, Andrea Pocar |
| 5: Charged Lepton Flavor Violation ($e$, $\mu$, $\tau$) | Sacha Davidson, Bertrand Echenard |
| 6: Dark Sector Studies at High Intensities | Stefania Gori, Mike Williams |
| 7: Hadron Spectroscopy | Richard Lebed, Tomasz Skwarnicki |

Frontier kickoff meeting: July 27, 2020, https://indico.fnal.gov/event/44121/

Index of all meetings: https://indico.fnal.gov/category/1102/

# Facilities and Experiments

- Large Hadron Collider and its high-luminosity upgrade, LHCb, CMS, ATLAS, and upgrades thereof
- SuperKEKB/Belle II ($e^+e^-$ beauty factory)
- BESIII ($e^+e^-$ charm factory)
- Proton Improvement Plan-II (PIP-II) at FNAL
- Proposed super-tau-charm factories
- Proposed circular and linear high-energy colliders
- NA62 at CERN (rare kaon decays)
- KOTO at J-PARC (rare kaon decays)
- Proposed REDTOP, JEF experiments ($\eta$, $\eta'$ factories)
- Neutron lifetime experiments (beam experiments, e.g. at J-PARC, ultracold neutron storage experiments)
- Muon and electron magnetic dipole moment experiments (Fermilab E989, J-PARC E34, ACME, ...)
- Electric dipole moment experiments (neutron EDM at Spallation Neutron Source, atomic and molecular EDM experiments, ...)

# Facilities and Experiments

- Antiproton/antihydrogen experiments (ASACUSA, ALPHA, BASE, GBAR, AEgIS, ALPHA-g, ...)
- Parity-violating electron-proton scattering experiments (PVIDIS/MOLLER/SOLID at JLab, P2 at MESA, ...)
- Parity violation in atoms and molecules
- Neutrinoless-double-beta-decay experiments (Kamland2-Zen, SNO+, NEXT-100, Legend-200, Cuore, US DOE tonne-scale program, ...)
- Proton decay experiments (JUNO, DUNE, Hyper-K, ...)
- Neutron-antineutron oscillation experiments (Oak Ridge development, ESS, DUNE, Super-K, ...)
- Mu2e, COMET (search for $\mu^- N \to e^- N$ and $\mu^- N \to e^+ N(Z-2)$)
- MEG-II (search for $\mu \to e\gamma$)
- Mu3e (search for $\mu \to eee$)
- Proposed TauFV (search for $\tau \to \mu\mu\mu$ and others)
- Searches for dark sectors at high intensities (many of the experiments already mentioned plus LDMX, CODEX-B, Mathusla, SHiP, KLEVER, ...)

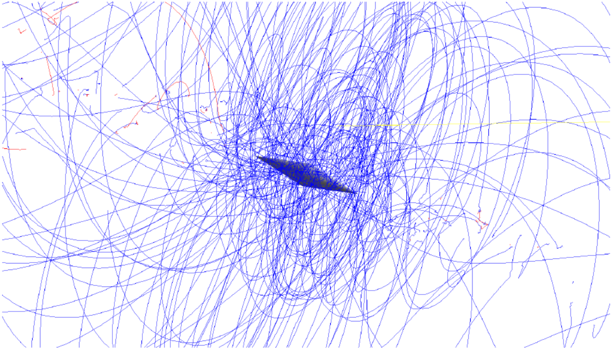
# Computing challenges

Experiments with high-intensity beams and/or complex detectors also produce high intensities of data that need to be processed, stored, and interpreted.

# Example 1: CLFV searches with muons (e.g. $\mu \to eee$)

Future CLFV experiments will deal with flux $> 10^{10}$ ($10^{12}$) muons/s for decay (conversion) experiments. In that regime, it will be necessary to quickly reconstruct tracks in very high multiplicity environments for triggering, and improve track reconstruction for data analysis.

[B. Echenard, private communication]



[Figure: N. Berger at July 2 RF5 Snowmass workshop]

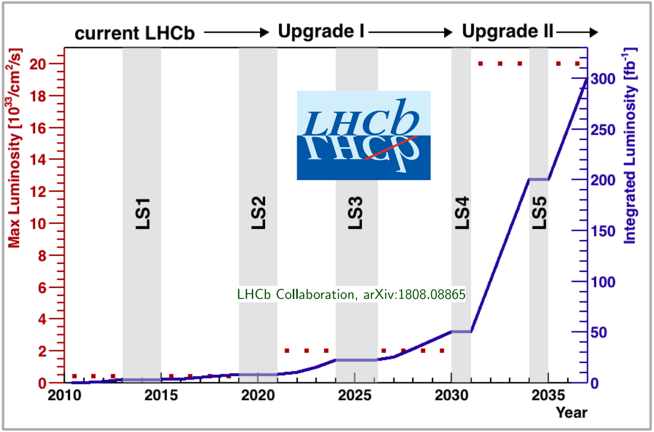
# Example 1: CLFV searches with muons (e.g. $\mu \to eee$)

The following are needed:

- Parallelization of track reconstruction algorithms with GPU and/or FPGA for fast triggering,
- Track reconstruction improvement with ML algorithms (better pile-up rejection, momentum resolution, ...),
- Improved MC simulation in the MeV - GeV energy range (e.g. Geant4),
- Development of adverserial NN for fast MC generation.

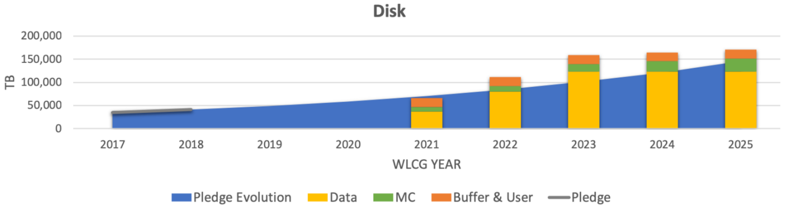
[B. Echenard, private communication]

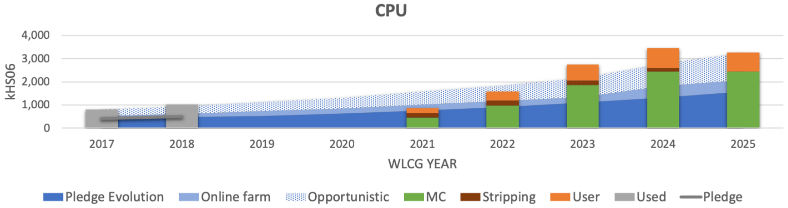
# Example 2: LHCb



# Example 2: LHCb

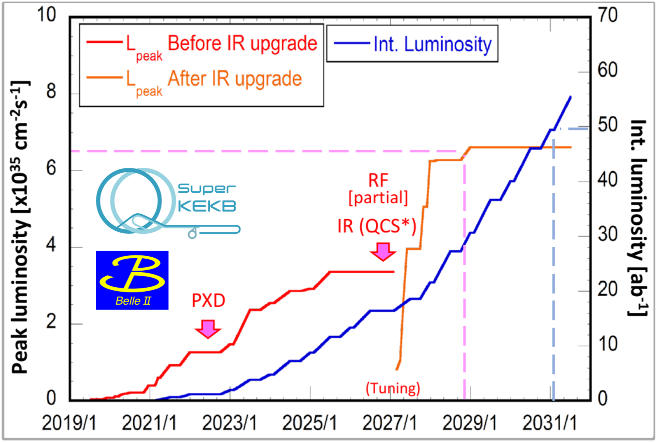
Real data dominate storage but Monte-Carlo simulations dominate CPU usage.
[LHCB-TDR-018]




The DIRAC THE INTERWARE framework is used for distributed computing.

# Example 3: Belle II



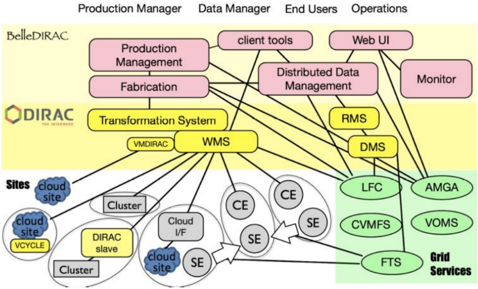
# Example 3: Belle II

## Belle II Computing Challenge

Study the properties of B mesons

981 members
118 institutes
26 countries

70 storage areas
130 PB of raw data
with 2 replicas



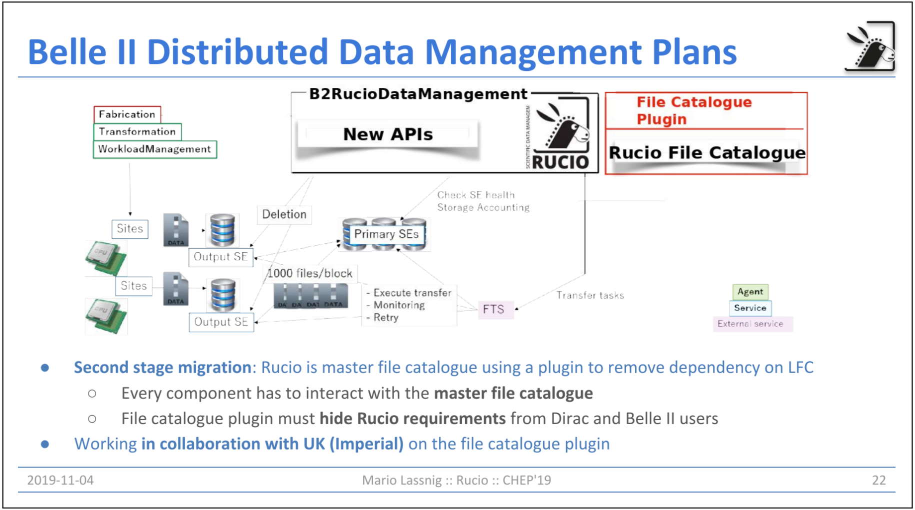

Physics data taking Phase 3 started this year

2019-11-04 Mario Lassnig :: Rucio :: CHEP'19 19

[M. Lassnig, talk at CHEP 2019]

# Example 3: Belle II

Work is underway to migrate the distributed data management to RUCIO, which is also used by ATLAS, CMS, DUNE, and many more experiments.




[M. Lassnig, talk at CHEP 2019]

# Example 3: Belle II

## Jupyter Integration - basf2

File Edit View Insert Cell Kernel Widgets Help | Not Trusted | Python 3 (Belle2)

Run | Markdown | Enter/Exit Live Reveal Slideshow

simulation for many events lasts very long. Therefore, I provide an input file for you. It is filled with 1000 pregenerated $B \to J/\psi\ K_s$ events that we will use for further processing. We will perform a typical analyis in this data sample:

In [ ]:

```python
import basf2
from modularAnalysis import *
from variables.utils import create_aliases_for_selected
file_name = "http://ekpwww.physik.uni-karlsruhe.de/~nbraun/B2JpsiKs_mu_BGx0_r1000.root"
filelistSIG = [file_name]

main_path = create_path()
queue = handler.create_queue()

inputMdstList("default", filelist=filelistSIG, path=main_path)

fillParticleList('pi+:loose', 'piid > 0.01', path=main_path)
fillParticleList('mu+:loose', 'muid > 0.01', path=main_path)

# reconstruct Ks -> pi+ pi- decay
# keep only candidates with 0.4 < M(pipi) < 0.6 GeV
reconstructDecay('K_S0:pipi -> pi+:loose pi-:loose', '0.4 < M < 0.6', path=main_path)

# reconstruct J/psi -> mu+ mu- decay
# keep only candidates with 3.0 < M(mumu) < 3.2 GeV
reconstructDecay('J/psi:mumu -> mu+:loose mu-:loose', '3.0 < M < 3.2', path=main_path)

# reconstruct B0 -> J/psi Ks decay
# keep only candidates with 5.2 < M(J/PsiKs) < 5.4 GeV
reconstructDecay('B0:jspiks -> J/psi:mumu K_S0:pipi', '5.2 < M < 5.4', path=main_path)

# perform B0 kinematic vertex fit using only the mu+ mu-
# keep candidates only passing C.L. value of the fit > 0.0 (no cut)
vertexRave('B0:jspiks', 0.0, 'B0 -> [J/psi -> ^mu+ ^mu-] K_S0', path=main_path)

# build the rest of the event associated to the B0
buildRestOfEvent('B0:jspiks', path=main_path)

# perform MC matching (MC truth asociation). Always before TagV
matchMCTruth('B0:jspiks', path=main_path)
```

[D. Dossett, talk at CHEP 2019]

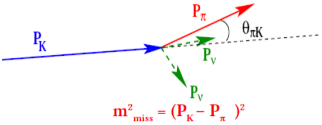
Comment from Paul Laycock (BNL): *The declarative coding style means it's much easier to hide the backend. Can this be extended to full-scale analysis?*

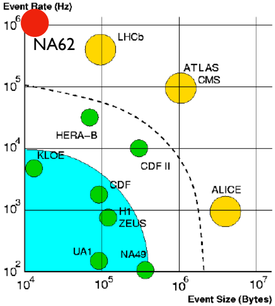
# Example 4: NA62

## NA62 experiment: $K^+ \to \pi^+ \nu \bar{\nu}$

$BR(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$

- New ***in-flight decay*** technique
- Collect $10^{13}$ kaon decays, measure BR to 10%




- Precision kinematic reconstruction
- Precision PID
  - upstream K
  - downstream e, $\mu$, $\pi$
- GHz rates mean precise timing:
  - ~100ps between sub-detectors
- Hermetic $\gamma$ detection
- $10^7$ $\pi^0$ (from $K^+ \to \pi^+\pi^0$) suppression
- $10^7$ $\mu$ suppression



[P. Laycock, talk at CHEP 2018]

# Example 4: NA62

## Data reduction

$K^+ \rightarrow ?$


| events / day (billions) | raw data / day (TB / day) | reco data / day (TB / day) | filtered reco / day (TB / day) |
|---|---|---|---|
| *~1* | *10* | *20* | *10 (~ 10 * 1)* |

- Unit of data-taking is an SPS burst (spill), which lasts 3.5 seconds
  - 250k events per burst, take 4000 SPS bursts / day
  - Event size of ~10kB, ~2.5 GB per burst
- Fully reconstructed data in NA62 ~twice the size of raw (similar to ATLAS ESD), not kept
- Reconstructed data is filtered to reduce data volume by ~20, writing ~10 filters
  - ~200 physicists on NA62 start with filtered datasets



[P. Laycock, talk at CHEP 2018]

# Lattice QCD

Lattice QCD calculations are essential for many projects in our frontier (e.g. quark flavor physics, hadronic corrections to muon $g-2$, nucleon structure) and require exascale high-performance computing.

There is a Snowmass topical group on lattice gauge theory, with conveners Zohreh Davoudi, Taku Izubuchi, and Ethan Neil:
https://snowmass21.org/theory/lattice

Also see the presentations by Steven Gottlieb, Andreas Kronfeld, Peter Boyle, and Phiala Shanahan at this workshop.